CONTEMPORARY INTERSTELLAR METEOROIDS IN THE SOLAR SYSTEM - IN SITU MEASUREMENTS AND CLUES ON COMPOSITION

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ABSTRACT

Meteoroids originating from the local interstellar medium, traverse the solar system. This has been proven by in situ measurements by interplanetary spacecraft as well as highly sensitive radar measurements. Early attempts to detect interstellar meteoroids using the instruments on board the Pioneer 8 and 9 spacecraft failed. More sensitive detectors on board the joint ESA/NASA mission Ulysses as well as on board the NASA spacecraft Galileo, however, unambiguously detected meteoroids of interstellar origin. This discovery has started efforts to compare the results from the in situ measurements with highly sophisticated models of interstellar dust properties derived from astronomical absorption and extinction measurements. It was found that, at least locally, is more mass locked up in meteoroids than expected from the astronomical measurements. So far the in situ measurements only allow to derive composition information indirectly via the meteoroid's dynamics.

Key words: dust; interstellar; in-situ measurements.

1. SOURCES OF METEOROIDS IN INTERPLANETARY SPACE

Our Solar System is filled with small solid fragments, meteoroids, that originate mainly from larger objects [1]. Asteroids collide with each other and produce large amounts of meteoroids [e.g., 2]. Existing meteoroids impact larger bodies and create more meteoroids. Comets disintegrate due to solar heating, releasing gas as well as solid fragments [e.g., 3]. But not only Solar System objects are sources of solid particles in the vicinity of the Sun. Meteoroids, that are known to exist in our galaxy [4], enter the Solar System from its local interstellar environment, and traverse it on unbound trajectories [5]. Depending on their size, they interact differently with the gravity and electromagnetic fields of the heliosphere. Table 1 gives an overview of the sources of meteoroids in interplanetary space.

In this work an overview is given of the in situ measurements of meteoroids originating from the interstellar medium. Also, first hints regarding their composition are discussed. The advantage of in situ measurements using detectors on board interplanetary spacecraft is that the object is analysed without the contaminating effects of the Earth. The meteoroids' orbits are preserved until just before impact, and can, theoretically, be determined with infinite precision. There are no changes to the shape or chemistry of the meteoroid due to an entry into an atmosphere. However, because of the limited size and mass of in situ detectors, so far only rough orbit determination has been possible and the area of chemical analysis by mass spectroscopy has just started [6, 7]. While the comparison of the in situ results with isotopically anomalous meteoritic inclusion is interesting, a full discussion on the latter is out of the scope of this work. Also, the solid matter that is observed by astronomical means in cold molecular clouds of our and other galaxies is not discussed in detail here, despite the fact that it is obviously connected to the local interstellar meteoroid population.

Table 1. Sources of meteoroids in interplanetary space.

source	characteristics	
	orbit	particle
Asteroids	low eccentricity, low inclination	silicate-type, compact
Comets	high eccentricity, random inclination	carbonaceous, fluffy
Edgeworth-Kuiper belt	low eccentricity, low inclination	unknown
Interstellar medium	hyperbolic	unknown

2. DUST IN THE LOCAL INTERSTELLAR MEDIUM

The local interstellar medium (LISM) is immersed in a bubble of very hot (10^6 K) and very tenuous (10^{-3} atoms cm^{-3}) galactic matter [8, 9]. Numerous clouds are present in this bubble, one of which is the local interstellar cloud [LIC, 10] that surrounds the Sun. Another example is the G-cloud in which the nearby star α Cen is located. It is believed [11] that the Sun will soon leave the LIC and enter the G-cloud. Figure 1 shows the

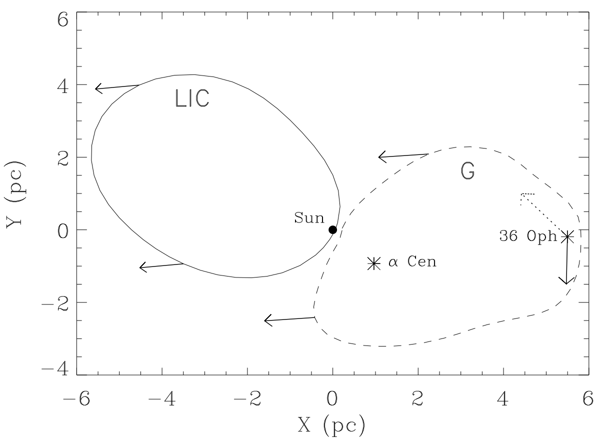

Figure 1. Sketch of clouds in the local interstellar medium as shown by Wood et al. [11] in their figure 2. A $10 \times 10\,\mathrm{AU}$ *region of the galactic plane is shown with arrows indicating the heliocentric velocities of the clouds. The local interstellar cloud (LIC), at the edge of which the Sun is located, is indicated by the solid line boundary. According to the Wood et al. model, the Sun will leave the LIC in the near future and will enter the G-cloud (indicated by the dashed line). The nearby star 36 Oph has a proper motion such that its velocity vector relative to the G-cloud (dotted line), and thus its astrosphere, has an angle with the line of sight towards the Sun.*

situation.

All material that reaches the Solar System from interstellar space is per definition part of the LIC. The properties of the LIC are summarised in table 2. The LIC is a typical warm, partially ionised diffuse cloud [12]. In the diffuse clouds solid material is normally subject to destruction processes, returning condensible elements like carbon, oxygen, nitrogen, as well as silicate, iron, magnesium etc. to the gas phase [13]. The analysis of the elementary composition of the LIC [14] shows that the mass fraction of solid to gaseous material should be between $1:500$ and $1:400$ [15].

Table 2. Properties of the Local Interstellar Cloud (LIC) according to Frisch et al. [15].

neutral Hydrogen density	$0.22\,\mathrm{cm}^{-3}$
ionised Hydrogen density	$0.10\,\mathrm{cm}^{-3}$
motion relative to the Sun	$\lambda = 74.7°$
(ecliptic coordinates)	$\beta = -4.6°$
temperature	$6900\,\mathrm{K}$
magnetic field	few μ G
average mass density	$2 \times 10^{25}\ \mathrm{cm}^{-3}$

The dust content of more remote interstellar clouds can be determined by measurements of the extinction of starlight passing through the cloud [4]. Typically a wavelength-dependent extinction is observed, caused by solid particles smaller than the wavelengths of the optical band. The concentration of larger grains can however not be determined this way, because they absorb and reflect light independent of the wavelength. The lines of sight through the LIC are too short to exhibit significant extinction. The emission of infrared radiation is also below any instrument's sensitivity. It is therefore impossible to observe solid particles in the LIC directly using remote sensing.

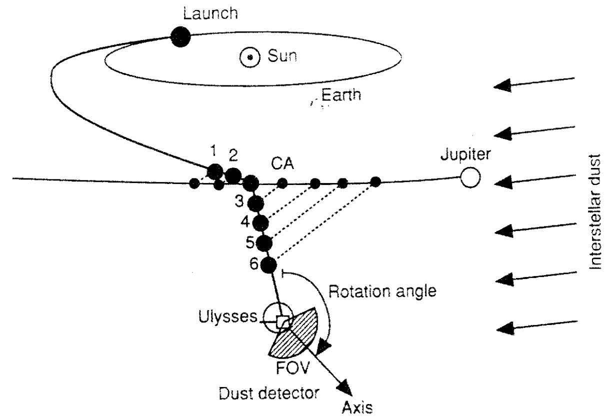

Figure 2. Ulysses measurements of the stream of interstellar meteoroids (entering from the right). A view from above the ecliptic plane is shown with the orbits of the Earth, Jupiter, and the Ulysses spacecraft. The big labelled dots indicate the positions of Ulysses during measurements of dust streams emanating from the Jovian system before and after the fly-by. The field of view (FOV) of the meteoroid sensor on board Ulysses is indicated by the hashed area. The instrument rotates about the spacecraft's spin axis and thus the impact rotation angle for each detected meteoroid can be measured. Most impacts after Jupiter fly-by (disregarding Jovian dust streams) have been detected at rotation angles around $90°$. *Figure taken from Grün et al. [16].*

3. THE EXISTENCE OF LOCAL INTERSTELLAR METEOROIDS

Whether or not local interstellar meteoroids exist and whether they penetrate the solar system was extensively discussed in the 1970ies and 1980ies. The Earth orbiting Pioneer 8 and 9 spacecraft that carried instruments for the detection of impacts by meteoroids did not find any unambiguously interstellar impactors. It was concluded [18] that less than 4% of the meteoroids found at 1 AU can be of interstellar origin. This was explained by modelling efforts [19, 20] that showed that the heliospheric magnetic field was able to divert solid particles, as long as their are not larger than $0.1\,\mu\mathrm{m}$, which was then believed to be the upper size limit of interstellar meteoroids [21] in the diffuse interstellar medium. At that point it seemed to be clear that no interstellar meteoroids can make it into the Solar System.

An argument derived from a work by Holzer [12] revived the discussion about the existence of solid interstellar matter in the Solar System: On average 1% of the mass of the interstellar medium is contained in dust. If that is true for the LIC, with its average mass density of

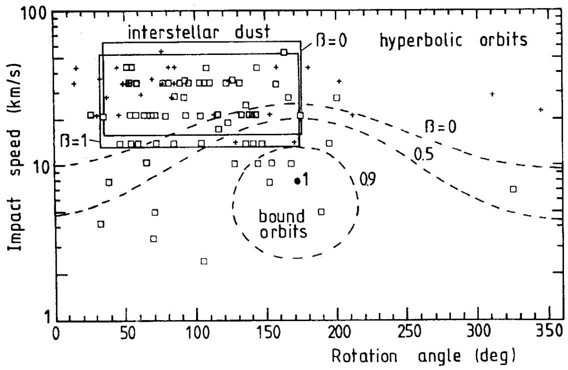

Figure 3. Impact speed and rotation angle of meteoroids detected by Ulysses after Jupiter fly-by. Crosses mark impact speed and rotation angle of meteoroids with masses below $10^{-13}\,\mathrm{g}$, squares represent meteoroids with masses above $10^{-13}\,\mathrm{g}$. The two boxes indicate the uncertainties in the measurement of the impact direction and velocity around the expected values for interstellar meteoroids of $26\,\mathrm{km\,s^{-1}}$ and $100°$ for two values of radiation pressure coefficient β. The dashed lines indicate the boundary between bound and unbound orbits, for different values of β, where $\beta = 0$ means no radiation pressure, and $\beta = 1$ means radiation pressure equals gravity. Figure taken from Grün et al. [17].

$2 \times 10^{-25}\,\mathrm{g\,cm^{-3}}$ and its relative velocity of $26\,\mathrm{km}^{-1}$ with respect to the Sun, an interstellar meteoroid flux density of $10^{-3}\,\mathrm{m^{-2}\,s^{-1}}$ can be expected. However, the flux at Earth of meteoroids with masses greater than $10^{-13}\,\mathrm{g}$ was found to be $1 \times 10^{-4}\,\mathrm{m^{-2}\,s^{-1}}$ [22], one order of magnitude lower than the value derived from the theoretical mass density of the LIC. The discussion on the existence of interstellar meteoroids was settled by the unambiguous detection of small interstellar particles (masses if typically $10^{-13}\,\mathrm{g}$) by an instrument on board the Ulysses spacecraft after its fly-by of Jupiter [16].

The evidence of the interstellar origin of the meteoroids detected by Ulysses comes from three independent observations: (a) The majority of impacts after Jupiter fly-by came from a retrograde direction, opposite to the direction of motion of meteoroids from Asteroids and short-period comets, (b) the impact velocity of particles from the retrograde direction was higher than the local solar system escape velocity, even if radiation pressure effects are neglected, and (c) the rate of impacts from that direction stayed nearly constant over a range of ecliptic latitude from $0°$ to $79°$. Observation (a) is illustrated in figure 2, showing the geometry of the measurements after the fly-by of Jupiter. Most meteoroids were detected at rotation angles around $90°$. This means that the observed meteoroids can only be of Solar System origin if a majority of them moves on retrograde orbits, which contradicts meteor observations. Observation (b) shows that the orbits of the detected meteoroids have to be hyperbolic. Due to the uncertainty in the measurement of the impact velocity, this statement does not hold for individual impacts, but for the statistic ensemble of impacts measured from the retrograde direction after Jupiter fly-by (see figure 3).

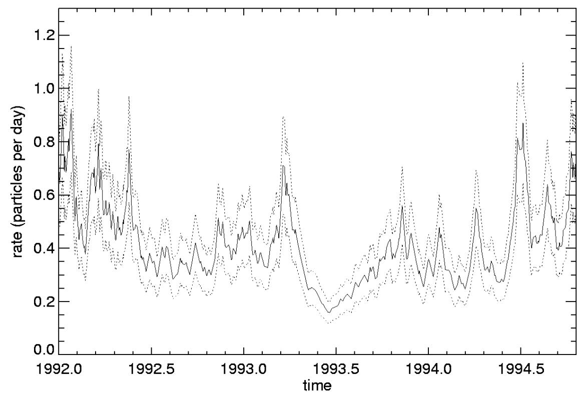

Figure 4. Impact rate of meteoroids measured by the detector on board the Ulysses spacecraft from 1992 to end-1994. A sliding mean average over 4 impacts is shown (solid line), together with 1σ uncertainties (dotted lines). Ulysses left the ecliptic plane at 1992.2 towards increasing ecliptic latitudes until end-1994. Figure taken from Baguhl et al. [23]

A stream of interstellar meteoroids penetrates the whole Solar System and must thus be detectable independent of ecliptic latitude. Observation (c) shows that this is true for the Ulysses observations. The impact rate from all impacts (interstellar plus interplanetary) is shown in figure 4. While it is true that the rate decreases by less than a factor of 3 after the spacecraft leaves the ecliptic plane (February 1992), it levels off above 0.3 impacts per day. If only meteoroids of Solar System origin were detected, the decrease in impact rate would have decreased by more than an order of magnitude. In combination, observations (a), (b), and (c) are considered evidence for the existence of interstellar meteoroids in the Solar System.

4. CHARACTERISTICS OF THE LOCAL INTERSTELLAR DUST POPULATION

The Ulysses spacecraft continues to monitor the stream of interstellar meteoroids. From these observations three discoveries have been made: (1) the particle mass distribution is not cut off at $10^{-13}\,\mathrm{g}$ as expected from extinction measurements [24], which leads to an apparent excess in dust mass and thus the dust-to gas ratio of the LIC by at least a factor of 2, (2) solar radiation pressure does affect the stream inside $4\,\mathrm{AU}$ [25], and (3) the flux of small interstellar meteoroids is modulated with the solar cycle [26]. In what follows the three phenomena and their consequences are discussed.

The mass density-mass distribution of the interstellar meteoroids measured by the the Ulysses detector as well as an identical instrument on board the Galileo spacecraft is shown in figure 5. The comparison of this local distribution with the average distribution derived from extinction measurements [21] over long interstellar lines of sight contains three interesting observations. First, the mass density contained small interstellar meteoroids is lower in the local distribution than in the average inter-

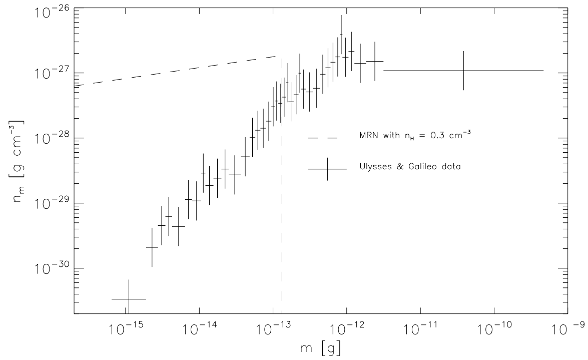

Figure 5. Mass density-mass distribution of interstellar meteoroids. The crosses represent the combined in situ measurements by the detectors on board the Ulysses and Galileo spacecraft. The dashed line shows the particle mass distribution of an model of the interstellar particle population derived from extinction measurements as well as cosmic abundance considerations [MRN, 21]. For this model it is assumed that the average gas density in the LIC is $0.3\,\mathrm{cm}^{-3}$.

stellar distribution. This was attributed to the effect of the solar wind magnetic field that deflects small interstellar meteoroids from the solar system [26]. Second, the mass range of interstellar meteoroids detected locally extends almost 4 orders of magnitude to higher masses than was expected from the average extinction measurements [27]. Since large particles with masses above 10^{-13} g do not cause a strong wavelength dependent extinction in the optical and UV bands, the observation of these grains does not directly contradict the extinction measurements. However, current models of the interstellar particle population [28, 29] feature a cut-off to large masses in the interstellar particle mass distribution, because they are constrained by the amount of condensible elements available in interstellar space. This leads to the third observation in figure 5. The total mass, which is given by the area beneath the curves in figure 5 locked up in local interstellar meteoroids is by about a factor of 2 bigger than expected from cosmic abundance considerations [15]. Thus, the in situ detection of relatively large ($m > 10^{-13}$ g) local interstellar meteoroids apparently violates the cosmic abundance of condensible elements. It can be speculated that the local interstellar meteoroids are injected into the LIC by some mechanism and thus do not contribute to the budget of chemical elements in the LIC. In that case the original source of local interstellar meteoroid population is still unknown.

The Ulysses measurements of the mass distribution of local interstellar meteoroids at different heliocentric distances shows that there is an interaction of the interstellar meteoroid stream with the solar radiation. Figure 6 shows the particle mass distribution of interstellar meteoroids measured by Ulysses at two different heliocentric distances. Meteoroids in the mass range between 10^{-17} and 10^{-16} kg are less abundant in the measurements closer to the sun (2 to 4 AU) than they are in the measurements more far away from the Sun (outside 4 AU). Starting with the assumption that the meteoroid mass distribution

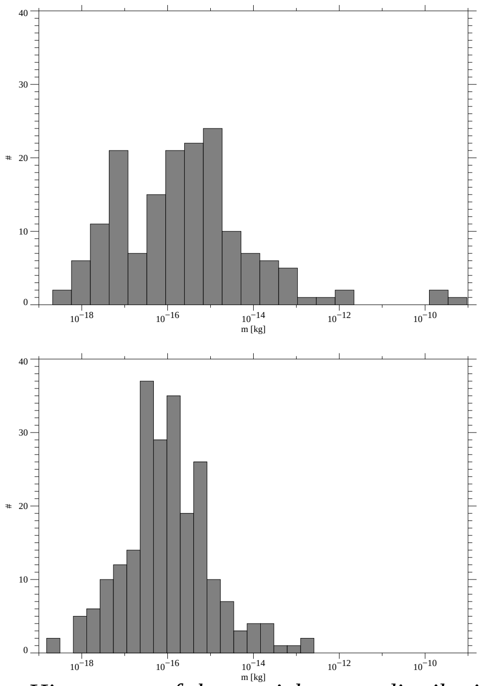

Figure 6. Histograms of the particle mass distribution measured by the Ulysses detector between 2 *and* 4 AU *(upper panel), and outside* $4\,\mathrm{AU}$ *(lower panel). In the upper panel a lack of particles between* 10^{-17} *and* $10^{-16}\,\mathrm{kg}$ *can be seen compared to the distribution in the lower panel.*

measured outside 4 AU is a better representation of the distribution in the LIC, it can be concluded that some mass-selective mechanism that is more efficient closer to the Sun removes the meteoroids in this mass region. The only mechanism that specifically affects meteoroids in the mass region between 10^{-16} and 10^{-17} kg is solar radiation pressure that is most effective for meteoroids that have sizes in the order of the maximum wavelength of the solar spectrum ($\lambda_{\max} = 450\,\mathrm{nm}$). While this observation depends on uncertain micro-physical properties of the meteoroids such as the bulk mass density and optical properties, it can be concluded that the material of which the local interstellar meteoroids consist can neither be too absorbent (like pure graphite) nor transparent (like pure quartz) [25, see also the paper by H. Kimura in this issue].

Another aspect of the Ulysses in situ measurements of interstellar meteoroids is the time variability of the interstellar stream. After Jupiter fly-by February 1992 until mid-1996 the interstellar particle flux appeared to be constant at $1\times10^{-4}\mathrm{m}^{-2}\mathrm{s}^{-1}$. Then the flux decreased significantly to $4\times10^{-5}\,\mathrm{m}^{-2}\,\mathrm{s}^{-1}$, about a factor of 3 below its former value (see figure 7). While it can not be ruled out that the reason for this decrease is a change in the local interstellar meteoroid concentration in the LIC, it is more likely due to the change in the phase of the solar cycle and thus in the heliocentric magnetic field configuration [30]. Modelling of the interaction of a constant stream of meteoroids, that acquire an electrostatic charge in interplanetary space, with the heliocentric magnetic field can account for this decrease of meteoroid flux in the Solar

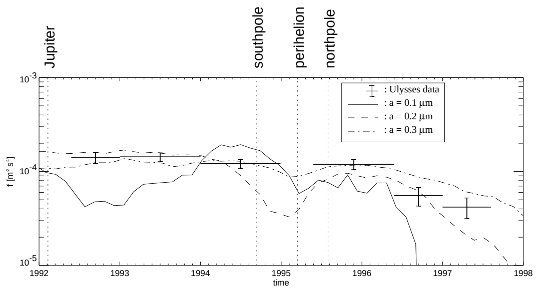

Figure 7. Time variability of interstellar meteoroid flux. The error-bars show the flux measured by the Ulysses detector and the lines indicate the flux predicted by the magnetic interaction model for various particle radii. Vertical lines indicate special events of the Ulysses mission. Figure taken from Landgraf [26].

System. The picture drawn by the model is the following: the magnetic field polarity between the solar maxima in 1980 and 1991 was favourable for focusing the interstellar meteoroid stream towards low heliographic latitudes, i.e. towards the magnetic equator of the Sun. Starting at the maximum in 1991, the magnetic field polarity was reversed, causing a deflecting action of the magnetic field. The average magnetic field strength at the beginning of a new cycle is not very strong, so the deflection started to be effective in 1995. Ulysses then consequently observed a decreasing flux in mid-1996 more than 1 year later due to the lag caused by the meteoroid's dynamics. The model curves in figure 7 fit reasonably well the measured flux values for spherical particles with radii of $0.2\ \mathrm{mum}$, corresponding to masses of $10^{-16}\ \mathrm{kg}$, the maximum in the particle mass distribution.

5. FUTURE MEASUREMENTS

After Ulysses and Galileo a new generation of meteoroid detectors was launched, one aboard the Cassini spacecraft [6] towards Saturn, and one aboard Stardust, a mission to collect cometary as well as interstellar meteoroids in situ [7]. While the Cassini detector is not expected to find many interstellar meteoroids due to the orientation of its trajectory downstream of the Sun, Stardust is specifically designed to collect and measure in situ interstellar particles. The collected particles will be available for analysis to the scientific community after the capsule returns to the Earth in 2006. The Cometary and Interstellar Dust Analyser (CIDA) instrument on board Stardust has detected few interstellar meteoroids so far, due to its small sensitive area of $80\ \mathrm{cm}^2$ and the reduced interstellar dust flux, as predicted [31]. The information content of these impacts is however high, because CIDA is capable of determining the elementary composition of the impactors.

The discussion in this paper shows that important information about our galactic neighbourhood is contained in the stream of interstellar meteoroids through the Solar System. From what we have learned so far new questions arise: what is the precise stream direction, and how close is it to the flow direction of gas from the LIC? Are there other interstellar meteoroid streams that also pass through the Solar System, but have lower flux densities so that the Ulysses detector can not identify them? What is the composition of local interstellar meteoroids and how does it compare to isotopically anomalous components of IDPs [32, 33, 34]? In order to find an answer to these questions new measurements have to be performed, because the Ulysses dust detector has a limited sensitive area ($0.1\ \mathrm{m}^2$) and limited direction, velocity and mass measurement accuracy. An ideal instrument for these measurements is a large-area, direction sensing, limited field of view detector as proposed by Grün et al. [35, see also the paper by Grün in this issue].

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